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Temperature, Humidity, and Wind Variations During Dissipation of a Low-Level Jet

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HENRY A. BROWN

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ABSTRACT

The time and height variations of temperature, wind speed, and moisture content observed at the Cedar Hill tower during the dissipation of a low-level jet on the morning of 14 May 1962 are presented and discussed. Three distinct stages of significant variations occur before sunrise at the upper levels of the tower. The three stages are: 1) a period of an abrupt and simultaneous warming and drying; 2) a period of steady temperature, mixing ratio, and wind speed; and 3) a period of pronounced decreases in temperature and wind speed and a marked increase in mixing ratio that occur progressively later with increasing height. It is proposed that these variations are produced by horizontal and vertical advection and by turbulent mixing.

1. Introduction

During the month of May 1962, the University of Chicago supplemented the basic instrumentation capable of measuring temperature and wind at 12 levels from 30 to 1420 ft on the Cedar Hill tower near Dallas, Texas, with six hygrothermographs at various levels. In addition, the University of Chicago maintained a small-scale triangular surface network surrounding the Cedar Hill tower on sites established by Texas A&M University (see Clayton, 1963), thus complementing the tower's vertical measuring capabilities with horizontal measuring capability.

Brown (1962) provided a comprehensive description of the field operation at and near the tower site conducted by the University of Chicago under the sponsorship of the U. S. Army Electronics Research and Development Laboratory. The University of Texas operated the Cedar Hill tower meteorological system under contract with the Air Force Cambridge Research Laboratories and a detailed account of the system has been given by Gerhardt *et al.* (1962).

In a previous report, Izumi (1964) discussed a warming phenomenon that occurred before and immediately after sunrise, followed by a marked cooling and pronounced reduction of wind speed at the upper levels of the Cedar Hill tower. Similar cases of early morning warming were recorded by the tower system during the first half of May 1962; of these the case of 14 May was most distinctive, in that the complete sequence of upper-level warming and ensuing cooling and reduction of wind speed occurred before sunrise.

The purpose of this paper is to describe the sequence of events that occurred before sunrise in the morning of 14 May 1962. This paper examines in detail the tower temperature, humidity, and wind data during

the period of interest and will propose explanations for the phenomena.

2. Synoptic situation

The U. S. Weather Bureau's Daily Weather Map for 0000 CST, 14 May 1962 reproduced in Fig. 1 is representative of the surface flow pattern for the night of 13-14 May. A stationary front extends south southwest from the northwestern edge of Kansas across the southeastern corner of Colorado into New Mexico and marks the boundary between the strong southerly flow of moist mT air to the east and dry cT air to the west. The sky cover observations from the stations in the Fort Worth-Dallas area near the Cedar Hill tower show scattered high clouds changing to clear skies during the period of interest.

The synoptic situation depicted is conducive to the development of a nocturnal low-level jet in the south central region of the United States. The wind field during the night shows an intense low-level jet stream developing in this region. At 0000 CST, a maximum wind speed of 76 mph is recorded at 5000 ft above mean sea level in the core of the jet stream centered near Oklahoma City.

3. Cedar Hill tower data

The Cedar Hill tower temperature and wind data presented here are based on continuous 10-min average readings. The humidity data were obtained from the hygrothermograph traces at 10-min intervals and are presented in the form of mixing ratios computed in the manner described by Brown (1962). The temperatures are in degrees Fahrenheit, the wind speed in miles per hour, and the mixing ratios in grams of water vapor

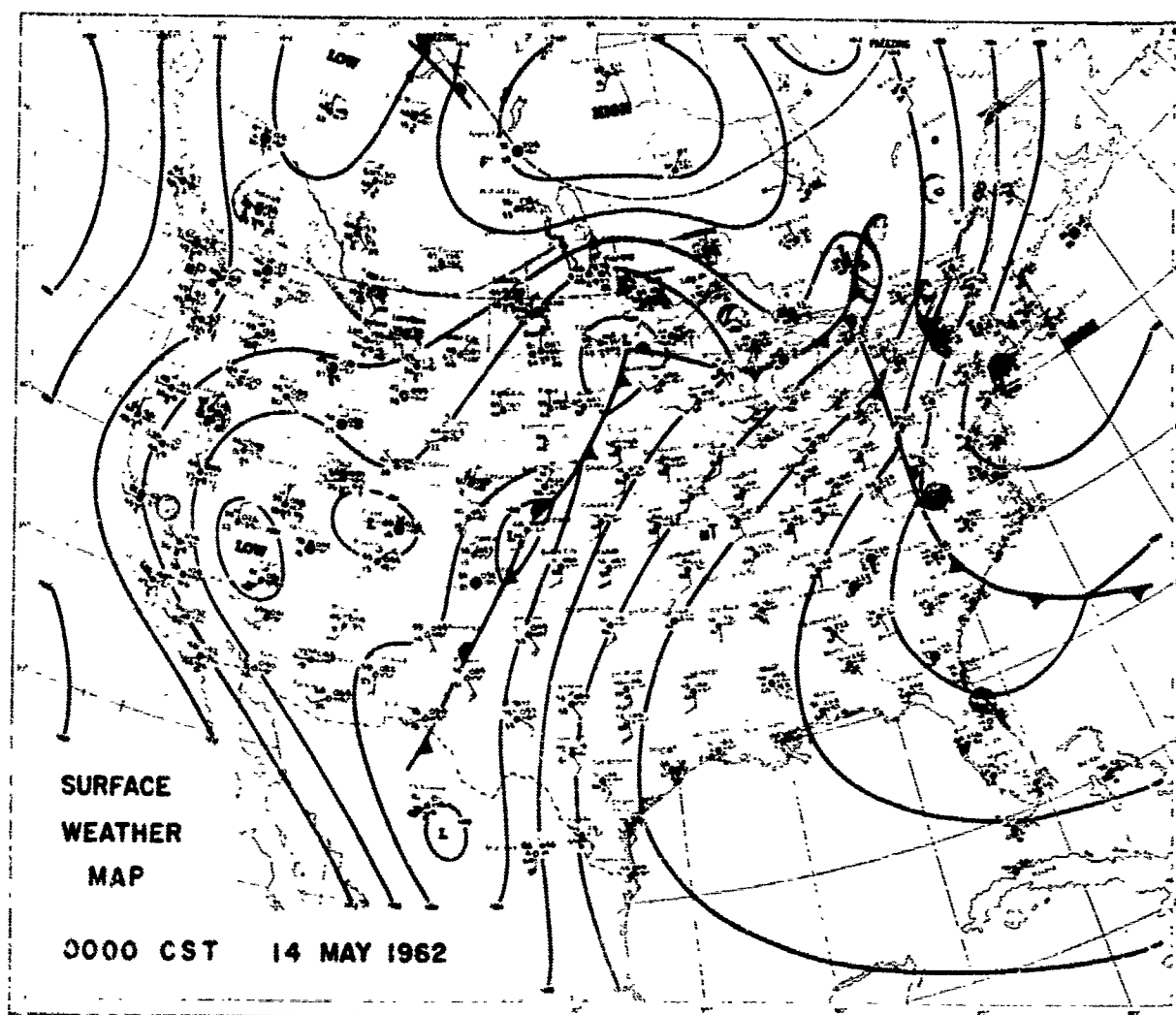


FIG. 1. Surface weather map for 0000 CST, 14 May 1962.

per kilogram of dry air. Central Standard Time is used throughout the discussion and the time of sunrise on 14 May is estimated to be 0529. No tower temperature and wind data are available for the 10-min periods beginning at 0000, 0010, and 0820 because these periods were devoted to calibration of the tower data acquisition and processing system.

The variation of temperature with time at the 12 levels on the tower from 2200, 13 May through 1000, 14 May is presented in Fig. 2. At 0050, the heretofore almost steady cooling at all the tower levels is interrupted by an abrupt and simultaneous rise in temperature at and above the 900-ft level. The upward trend of temperature lasts for only a short duration and while followed by a period of rather erratic temperature behavior at the 900-ft level, all levels above 900 ft reflect a long period of almost steady temperature. The steady period is then followed by a temperature decrease of varying rate at all levels—an extremely rapid rate of decrease at the upper levels, a significantly rapid rate of decrease discernible at 750 ft, and a continued gradual cooling at the lower levels. The beginning of marked temperature decreases occur at 0230 at 750 and 900 ft, 0310 at

1050 ft, and 0340 at the top three levels. The rate of cooling increases with height and the maximum cooling for a 10-min period is 5.8F at 1300 ft between 0340 and 0350. The decrease in temperature stops at about 0410 and the minimum temperature at all levels above 600 ft is attained at this time, which is 1 hr 20 min before sunrise.

Fig. 3 shows the variation of wind speed with time at the 12 levels on the tower for the comparable period as on the previous figure. A low-level jet which developed during the night reaches its maximum intensity of over 50 mph at 1300 ft by 2300. Thereafter the winds at all levels exhibit greater variability with time than the temperature; however, the over-all wind pattern for the upper levels of the tower show features generally similar to the temperature pattern. A perceptible increase in wind speed occurs at almost all the levels above 750 ft between 0050 and 0120 and this time corresponds to the brief period of temperature rise noted at these levels. At levels above 900 ft the wind speed then steadies and this steady period coincides with the long period of almost steady temperature. The subsequent major wind speed decrease at and above 750 ft occurs later

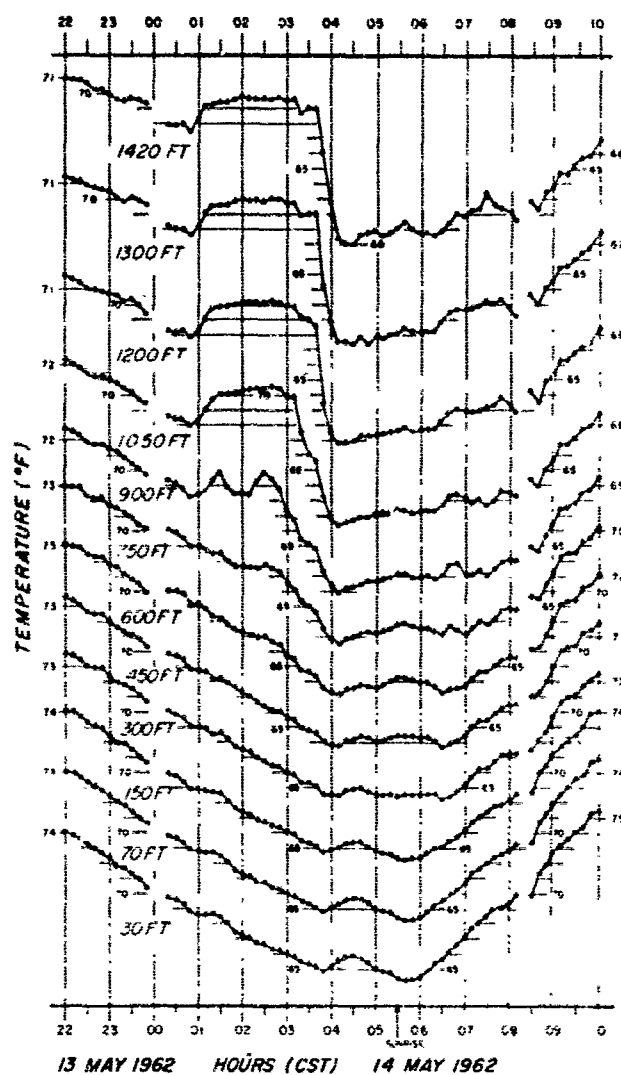


FIG. 2. Time variation of temperature at the 12 levels of the Cedar Hill tower from 2200 CST, 13 May to 1000 CST, 14 May 1962.

with increasing height and is almost simultaneous with the major temperature decrease at each of the levels. In conjunction with the changes in the wind speed the changes in the wind direction were examined. The time variation of wind direction showed almost a steady wind direction during this period at the middle levels of the tower between 600 and 900 ft, while the wind veered slightly and steadily at the upper levels of the tower.

The variation of mixing ratio with time accompanying the changes in temperature and wind speed is presented in Fig. 4. The mixing ratios are based not on 10-min averaged data but on instantaneous data reduced from the hygromograph charts. The notable features are the abrupt and marked decrease of mixing ratio to an almost constant value and the abrupt and marked increase that follows later at the levels of 1050 and 1420 ft. A small decrease and subsequent increase in mixing ratio are also noted at 750 ft. With the exception of 750 ft, the time of occurrence of decrease in mixing ratio corresponds to the time of occurrence of

the temperature rise. The marked increase in mixing ratio which starts at 0230 for 750 ft, 0320 for 1050 ft, and 0340 for 1420 ft is almost simultaneous with the sudden decrease of temperature and wind speed at these levels. As with the temperature and wind speed at 1050 and 1420 ft, the mixing ratio remains almost constant between the time of extreme changes in its values.

Fig. 5 depicts the evolution of the vertical profiles of mixing ratio (left), temperature (middle), and wind speed (right) during the period of interest between 0050 and 0400. The first set of profiles (Figs. 5a, b and c) presented at 20-min intervals illustrates the changes occurring during the period of upper-level warming and drying discussed previously. The temperature profile at 0050 (Fig. 5b) shows a slight increase of temperature with height up to 600 ft. Actually, the data show two weak inversions, one at the surface and another between 450 and 600 ft. The subsequent profiles indicate warming above and a relatively small rate of cooling below 750 ft. Between 0050 and 0110 the warming increases with height, while between 0110 and 0130 it decreases

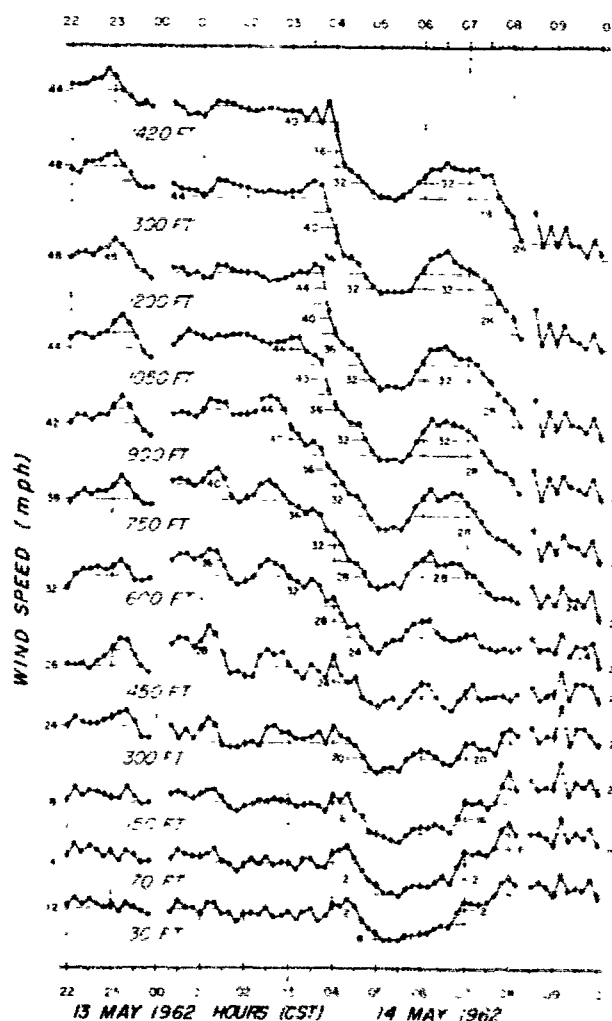


FIG. 3. Time variation of wind speed at the 12 levels of the Cedar Hill tower from 2200 CST, 13 May to 1000 CST, 14 May 1962.

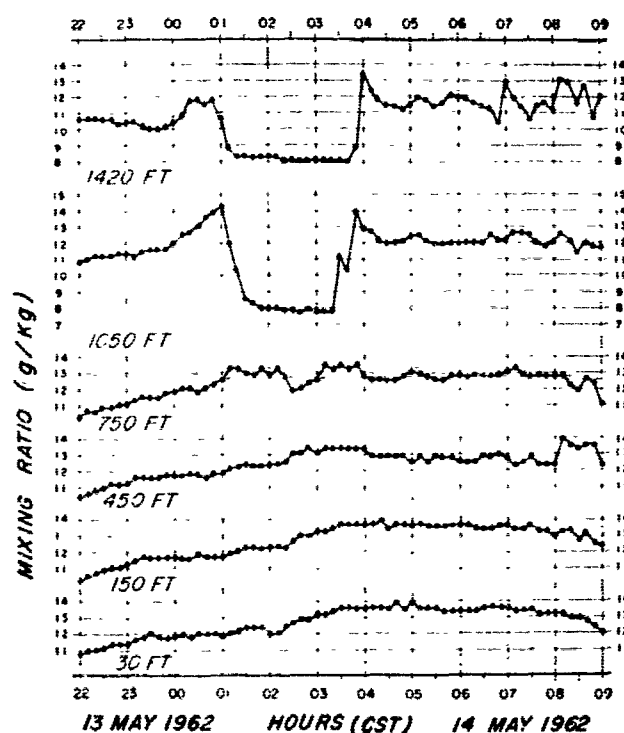


FIG. 4. Time variation of mixing ratio at six levels of the Cedar Hill tower from 2200 CST, 13 May to 1000 CST, 14 May 1962.

with height. Due primarily to the warming, the temperature inversion with its base at 450 ft deepens from 600 ft to 1050 ft by 0130. The mixing-ratio profiles (Fig. 5a) show the amount of drying above 750 ft to be the largest at 1420 ft between 0050 and 0110 and at 1050 ft between 0110 and 0130. The vertical distribution of wind speed (Fig. 5c) shows a jet-like profile with the height of maximum wind speed varying between 900 and 1200 ft during this period.

The next set (Figs. 5d, e and f) represents the profiles during the period of almost steady mixing ratio, temperature, and wind speed at the upper levels. The profiles of mixing ratio and wind speed (Figs. 5d and f) show little variation at all levels. However, the temperature profiles (Fig. 5e) show continual cooling below 900 ft which results in the intensification of the inversion between 450 and 1050 ft.

The last set of profiles (Figs. 5g, h and i) presented at 30-min intervals shows the changes in the profiles during the period of major increase of mixing ratio and major decreases of temperature and wind speed. The mixing-ratio profiles (Fig. 5g) show the progressive increase of mixing ratio from 750 ft and above until the vertical distribution becomes almost uniform with height by 0400. The temperature profiles (Fig. 5h) show cooling at all levels with the greatest amount of cooling occurring at the upper levels between 0330 and 0400. This cooling is accompanied by a rapid rise of the inversion which maintains its intensity of 0.7°F per 100 ft during the ascent. Below the base of the rising inversion the lapse rate does not become adiabatic but

remains subadiabatic. By 0410 (not shown) no trace of the inversion is found within the heights of the tower. The wind speed profiles (Fig. 5i) show no change below 450 ft, but a decrease in the wind speed starts at the levels between 600 and 900 ft and proceeds upward together with the rise of the temperature inversion. The level of maximum wind speed is seen to rise with the top of the rising inversion.

Further analysis of the tower temperature data revealed the following results. In Fig. 6 is shown the time and height variations of potential temperature and the upper and lower boundaries of the temperature inversions. The stippled areas represent the temperature inversions. The weak inversions between 450 and 600 ft which was described previously but was not clearly discernible in Fig. 5b exists between 0020 and 0110. At about 0100 the upper inversion appears within the heights of the tower and descends rapidly. The rapid descent of the top of the inversion is shown to be adiabatic. The descent of the base is even more rapid and due to the 10-min averaging process the descent shown in Fig. 6 can only be inferred. However, the descent of the base appears to be nonadiabatic. By 0110 the upper and lower inversions are no longer distinguishable as separate but as one inversion. At about 0230 the base and the top of the newly formed inversion begins to rise, slowly at first and more rapidly later. The rapid rise of the inversion is also shown to be adiabatic.

4. Discussion

The Cedar Hill tower data, comprised of temperature and wind observations at twelve levels and humidity observations at six levels, revealed three distinct stages of significant changes at the upper levels of the tower during the dissipation of a low-level jet before sunrise on 14 May 1962. The three stages which result in the evolution of the vertical profiles of temperature, mixing ratio, and wind speed are: 1) a brief period of an abrupt and simultaneous increase in temperature and decrease in mixing ratio; 2) a long period of almost no variation of temperature, mixing ratio, and wind speed; and 3) a period of marked decreases in temperature and wind speed and marked increase in mixing ratio that occur progressively later with increasing height. The profiles of temperature and mixing ratio, featureless at first with the parameters varying only slightly with height, are transformed into profiles that exhibit characteristics of a subsidence inversion and then revert to another set of featureless profiles with the temperature gradually decreasing with height and the mixing ratio almost constant with height.

The sudden and simultaneous warming and drying during the first stage is explained by the passage of a transition surface separating cool and moist air from warm and dry air. The temperature difference across the surface describing the transition is only about 2°F. However, the moisture discontinuity is extremely

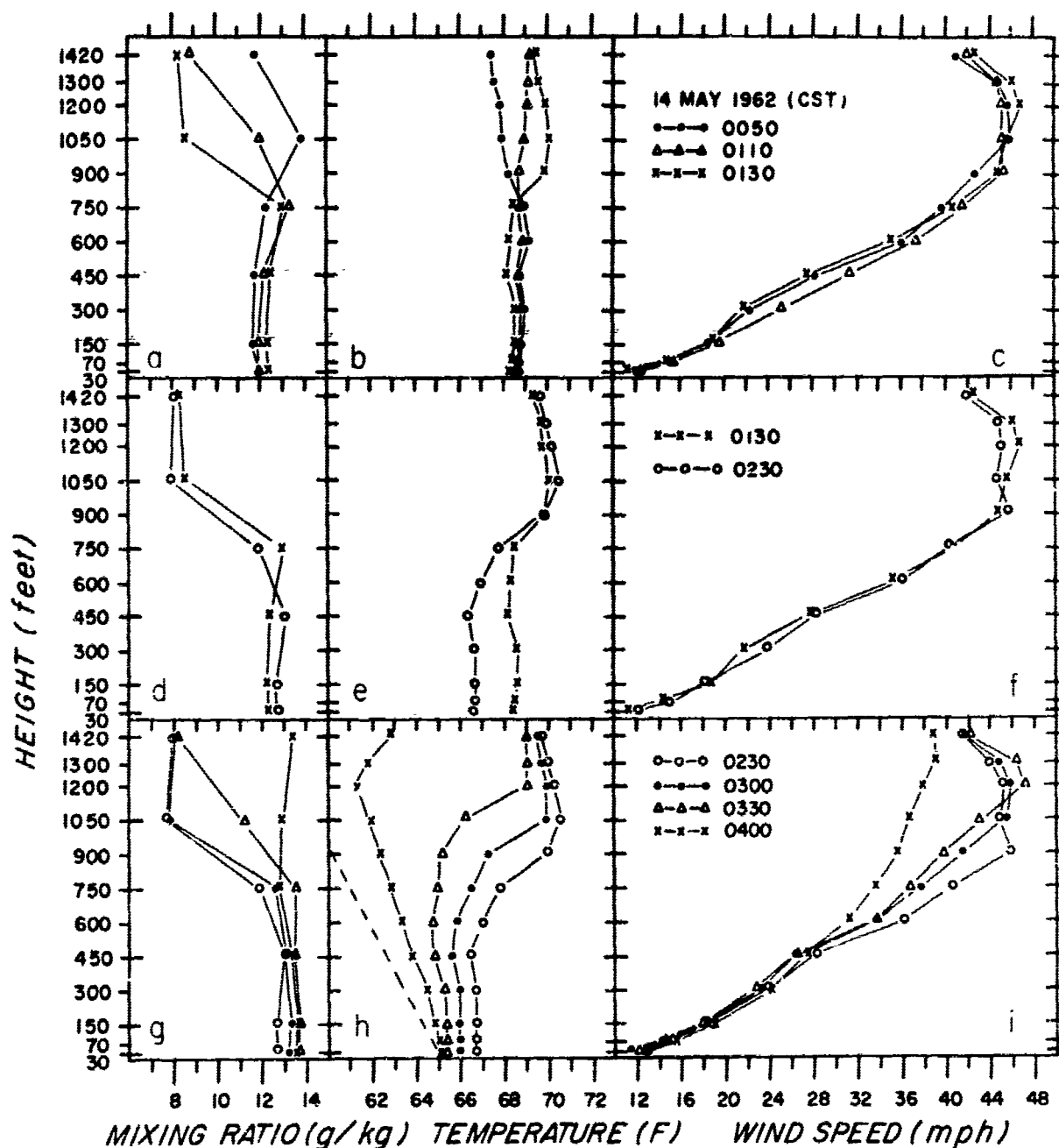


FIG. 5. Vertical profiles of mixing ratio, temperature, and wind speed observed at the Cedar Hill tower during the early morning hours of 14 May 1962. Dashed line in Fig. 5h represents dry adiabat.

sharp, with a change of mixing ratio from 14 gm kg^{-1} to 8 gm kg^{-1} occurring within a matter of 40 min at the 1050-ft level as shown in Fig. 4. The warming and drying together with the adiabatic descent of the top of the upper inversion shown in Fig. 6 suggest local subsidence or vertical advection. However, the extremely large decrease in mixing ratio in comparison with the small temperature increase and the nonadiabatic descent of the base of the upper inversion (Fig. 6) suggest that the upper-level warming and drying cannot be attributed solely to vertical advection but that horizontal advection must also be considered. For this reason, the changes in temperature and humidity are ascribed to vertical as well as horizontal advection of warmer and drier air at the upper levels of the tower.

Following the passage of the surface of transition the presence of uniform and stable air results in the almost unvarying temperature, moisture, and wind speed for a relatively long period of time during the second stage. Examples of the type of air envisioned to be present are illustrated by the temperature fields and, particularly, the moisture fields revealed from recent detailed observations made by low flying aircraft during daytime. Aircraft observations presented by Braham and Draginis (1960) and Staff Members, National Severe Storms Project, U. S. Weather Bureau (1963) showed pronounced wavelike perturbations in the temperature and moisture fields. Data analysis presented by Edinger (1963) showed overlapping tongues of moist and dry air above a marine layer. These studies suggest that

advection of air with heterogeneous distribution of moisture and of temperature could produce the changes in moisture and temperature as observed at the Cedar Hill tower.

During the third stage it is observed that at each level there are simultaneous occurrences of increasing mixing ratio and decreasing temperature and wind speed and that these changes occur progressively later with increase in height. This combined action can be explained by the upward progression of a turbulent mixing process as the layer of warm and dry air is destroyed or lifted by the mixing process. The turbulent mixing proceeds upward, slowly at first and more rapidly later. Accompanying the upward propagation of vertical mixing is the rise of the temperature inversion which maintains the same intensity. The base and the top rise adiabatically as shown in Fig. 6. The turbulent mixing process is thorough and effective as manifested by the marked and rapid changes that occur at the upper portions of the temperature, mixing-ratio, and wind speed profiles (Fig. 5).

The above sequence of changes in the temperature, moisture, and wind speed can be interpreted in terms of the Richardson number, Ri , defined by:

$$Ri = \frac{\frac{g}{T} \left(\frac{\Delta T}{\Delta z} + \Gamma \right)}{\left(\frac{\Delta v}{\Delta z} \right)^2 + \left(\frac{\Delta u}{\Delta z} \right)^2}$$

where g is the acceleration of gravity, T the temperature, Γ the dry adiabatic lapse rate, z the height, and v and u the horizontal wind components. The computed

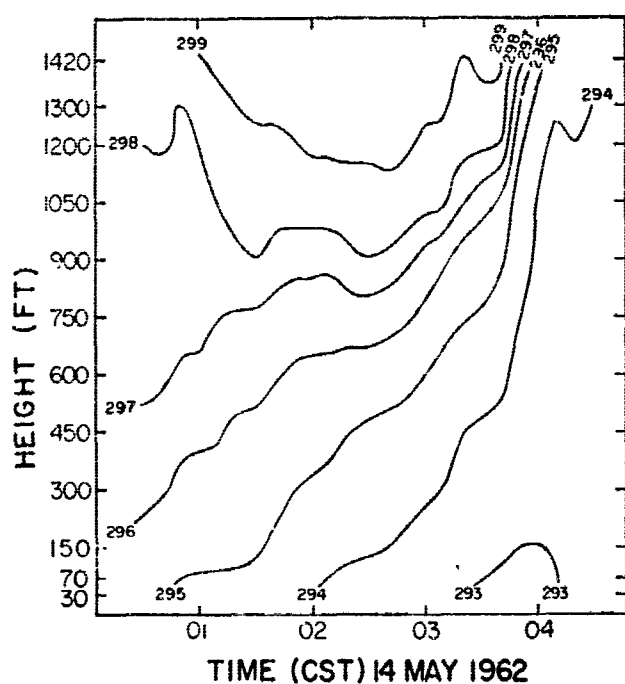


FIG. 6. Time and height variations of potential temperature and of the upper and lower boundaries of temperature inversions observed at the Cedar Hill tower during the early morning hours of 14 May 1962. Shaded areas represent temperature inversions.

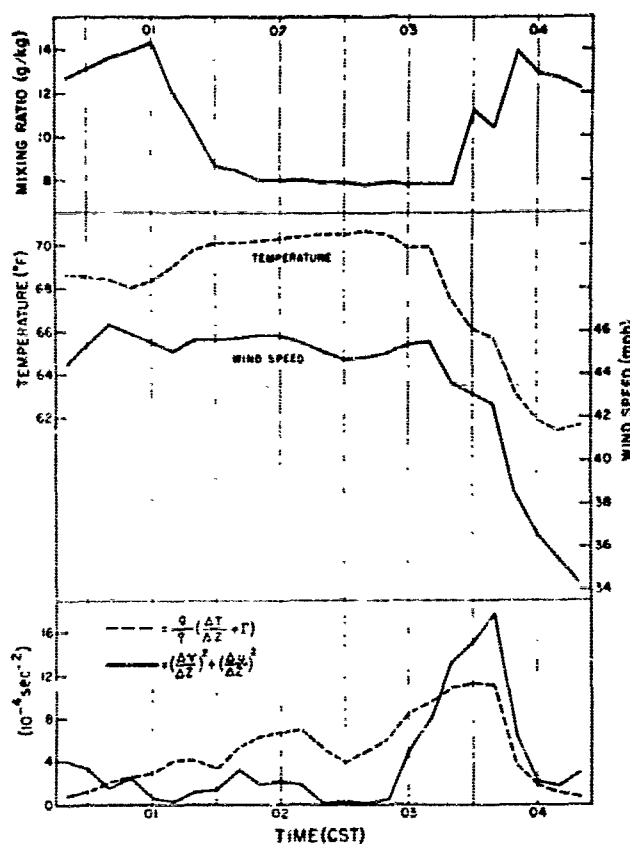


FIG. 7. Time variations of the numerator and denominator of the Richardson number, mixing ratio, temperature, and wind speed at 1050 ft of the Cedar Hill tower during the early morning hours of 14 May 1962.

values of the numerator and denominator of Ri obtained for the 1050-ft level are presented in Fig. 7 together with the changes in the mixing ratio, temperature, and wind speed at 1050 ft between 0020 and 0420. During the first stage the decrease in mixing ratio and the increase in temperature are accompanied by an increase in the temperature gradient and a decrease in the small wind gradient. The opposing changes in the temperature and wind gradients during the first stage and the almost steady mixing ratio, temperature, and wind speed during the second stage suggest a suppression of turbulence and it is apparent that $Ri > 1$. On the other hand, the marked increase in mixing ratio and the marked decreases in temperature and wind speed during the third stage suggest an intensification of turbulence and it is apparent that $Ri < 1$. Most significantly, the marked and simultaneous changes in the parameters at the start of the first and third stage occur when $Ri = 1$. Thus, at 1050 ft and during the specific period of interest, Ri of unity appears to be the critical value for the increase or decrease of turbulence as was originally implied by Richardson (1920). Similar conclusions were reached by Durst (1933) and Flower (1937) using continuous traces of wind speed and wind direction as turbulence indicators for layers near the ground.

As a supplement, the temperature sounding at Fort Worth, the nearest radiosonde station to the Cedar Hill tower, is presented in Fig. 8 together with the temperature profiles obtained from the tower during the rise of

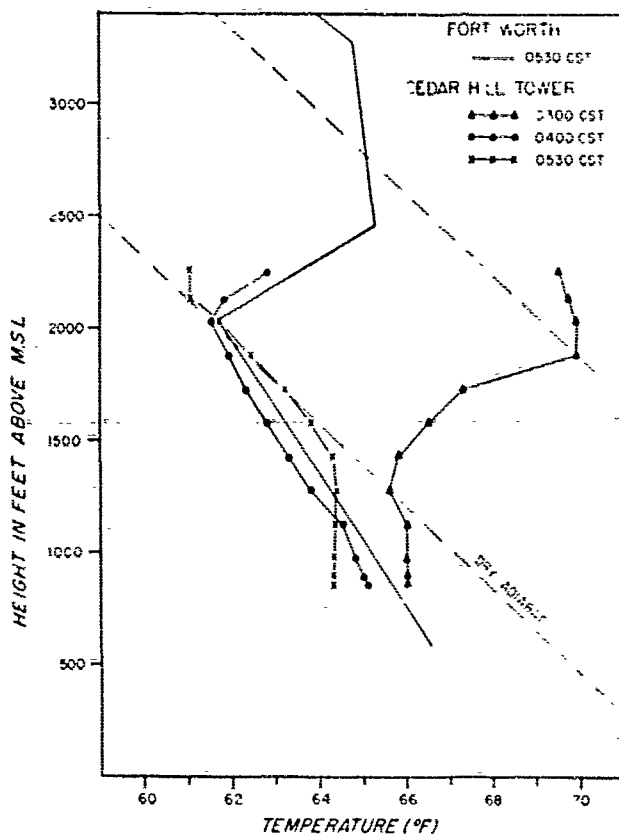


FIG. 8. Fort Worth temperature sounding for 0530 CST and Cedar Hill tower temperature profiles for 0300, 0400, and 0530 CST, 14 May 1962.

the inversion. The release time of the radiosonde is reported to be 0530. The tower temperature profile for 0400 is in good agreement with the Fort Worth sounding with respect to the temperature and height of the inversion base and with respect to the lapse rate below the inversion. Furthermore, the temperature gradient of the inversion at Fort Worth is 0.8F per 100 ft which is in agreement with the 0.7F per 100 ft obtained for the tower. Therefore, although there is a time difference of about one hour and a half, it appears that the inversions observed at the tower and at Fort Worth evolved in the same manner.

5. Conclusions

The detailed observations from the Cedar Hill tower revealed a warming phenomenon occurring before sunrise at the upper levels of the tower during the dissipation of a low-level jet on 14 May 1962. In the first stage the tower temperature and wind data supplemented with humidity measurements show the warming coupled with marked drying and slight increase in wind speed. This is followed by a second stage of long period of almost steady temperature, wind speed, and humidity. The final stage is characterized by pronounced decreases in temperature and wind speed and a pronounced increase in moisture content that occur progressively later with increasing height. It is most significant that these various stages occur before sunrise.

The warming results in the sudden appearance of an upper-level inversion that quickly combines with a weak middle-level inversion to form a single deep inversion. The base of the upper inversion is found to descend nonadiabatically while the top of the same inversion descends adiabatically. The subsequent lifting of the combined inversion is shown to be adiabatic.

Horizontal as well as vertical advection is proposed to be responsible for the upper-level warming and drying. Turbulent mixing is proposed to be responsible for the pronounced decreases in temperature and wind speed and the pronounced increase in mixing ratio.

The advantage of the height of the Cedar Hill tower over other meteorological towers and the advantage of continuous measurements over balloon soundings are clearly evident from the observations presented in this paper. Whereas the lower levels of the tower show only gradual changes in temperature, humidity, and wind speed the upper levels show sequences of significant changes. The entire sequence of events occurs before sunrise without the influence of any large scale disturbance, but the changes in the temperature, mixing ratio, and wind speed are as sudden and vigorous as the changes observed during daytime when convective activities are in progress or during passages of traveling disturbances.

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